EVALUATION AND REVIEW

Amendment to The Water Quality Control Plan for the Sacramento River and San Joachim River Basins – The Control of Nutrients in Clear Lake (Central Valley Regional Water Quality Control Board)

And

Total Maximum Daily Load for nutrients in Clear Lake, Lake County, California (Tetra Tech)

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Credentials and Qualification

The evaluator is a Chair Professor of Environmental and Water Resources Engineering at Northeastern University in Boston, MA. Prior to joining Northeastern in 2002 I was for 29 years a Professor at Marquette University in Milwaukee (WI) and President of AquaNova International, Ltd. in Mequon (WI). I hold a Diploma Engineering Degree from the Technical University of Brno (Czech Republic), which I received in 1963 and a Doctor of Philosophy Degree (Environmental and Water Resources Engineering) received in 1971 from Vanderbilt University, Nashville, Tennessee.

I have been involved in research on water quality management and control since 1963, i.e., I have more than thirty years of experience as a researcher, writer, and academian. I have also served as an expert witness in water quality and stormwater related litigations. I have published several professional books, including *Water Quality Management* (coauthored with P.A. Krenkel and published by Academic Press in 1980), *Handbook of Nonpoint Pollution: Sources and Management* (co-authored by Gordon Chesters and published by VanNostrand Reinhold in 1981) and *WATER QUALITY: Prevention, Identification and Management of Diffuse Pollution* (coauthored by H. Olem and published by VanNostrand Reinhold in 1994), *WATER QUALITY: Diffuse Pollution and Watershed Management* (published by J. Wiley in 2003) and co-authored *Diffuse Pollution : An Introduction to Problems and Solutions* (N. Campbell, B. D=Arçy, A. Frost, V. Novotny, A. Samson, published by IWA Publishing, London, UK, 2004). All books have been well received by professionals, who acquired them, and some have become texts in courses taught at other universities (e.g., Duke University, University of Kansas, University of North Carolina, University of Connecticut and others). I have also published over one hundred forty professional papers and more than hundred technical reports.

I was a member of two National Research Council Committees. Participation on the *Committee to Assess the Scientific Basis of the Total Maximum Daily Load Approach to Water Pollution Reduction* (National Research Council) in 2001 has a particular relevance to the issue of Clear Water TMDL. This committee has reestablished policies and guidelines of the national TMDL program after Congress temporarily halted its progress and charged NRC to define and reestablish its scientific basis.

Through Marquette University and Northeastern University I have received numerous grants sponsored by the National Science Foundation, US EPA, including two STAR watershed research grants and other agencies. Through my small consulting company (AquaNova International, LTD) I received two prestigious grants from the Water Environment Research Foundation, both dealing with water quality issues. The projects results are nationwide manuals on Use Attainability Analysis and abatement of winter snowmelt runoff. AquaNova also prepared a successful Use Attainability Analysis for the Lower Des Plaines River which is the largest effluent dominated stream in the world; carrying treated effluents and urban runoff from most of the Metropolitan Chicago area (9 million inhabitants). As a consultant I worked on many environmental problems such as remediation and restoration of receiving water bodies and development of Best Management Practices for control of diffuse pollution, including also evaluation of the impact of the water quality plan of the Sacramento Regional Sanitary District on the Sacramento River (2002). I was also retained by the Natural Resource Defense Council in New York as an expert assisting the council on issues related to water quality of reservoirs supplying water to the City of New York.

Finally, in 2003 I was elected to the International Water Academy (Oslo, Norway) and, in 2005, selected by eminence a Diplomate of the American Academy of Environmental Engineers.

The TMDL PROCESS

The TMDL (Total Maximal Daily Load) process links the development and implementation of control actions to the attainment of water quality standards. The objective of a TMDL is to allocate allowable loads of pollutants among different sources (point and nonpoint) so that appropriate control actions can be taken and water quality standards achieved. The TMDL development activities defined in the EPA guidelines[1] are:

- Selection of the pollutants to consider.
- Estimation of the water body assimilative capacity.
- Estimation of the pollution from all sources to the water body.
- Predictive analysis of pollution in the water body and determination of total allowable pollution load.

[1] *Guidance for Water Quality -based Decisions: The TMDL Process.* EPA 440/4-91-004, U.S. Environmental Protection Agency, Office of Water, Washington, DC

- Allocation (with a Margin of Safety) of the allowable pollution load among the different pollution sources in a manner that water quality standards are achieved.

The methodology described in the EPA guidelines presumes that the use of the water body and corresponding appropriate water quality standards have been defined and established. In a Water Body Assessment process, the agencies define the water bodies where the designated use is not met. The second premise of the TMDL is that the established standards are attainable which, according to the Clean Water Act, is established by a Use Attainability Study (40 CFR §131.10(j)) or Evaluation. In a more general sense, the TMDL process can be broken into the following tasks:

1. Define the use of the water body
2. Define the criteria which would define the use
3. By water body assessment determine whether the use is attained
    - if the use is attained antidegradation principles are applied to secure that the use is not impaired by future developments and discharges (40 CFR §131.12)
4. If the use is not attained the TMDL separates the receiving water bodies into those that are water quality limited and those that are effluent limited and develops the Total Maximal Daily Loads (TMDL) for the critical compounds.
5. The TMDL is allocated, minus the background load and Margin of Safety, among the regulated point sources and nonpoint sources where reduction of loads is feasible and achievable.

In addition to TMDL there is another statutory process that can be used to establish the goals and necessary steps to achieving these goals – the Use Attainability Analysis[2,3,4]. The Use Attainability Analysis (UAA) requirement stems from Section 101(a) of the Clean Water Act that states: *it is the national goal that* <u>*wherever attainable*</u>.. *water quality provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water to be achieved...* Consequently, the UAA study investigates whether the standards defining the designated use are attainable in the analyzed water body. If the statutory CWA use is not attainable, the UAA should define the most optimal attainable use for the water body.

In contrast, the Total Maximum Daily Load (TMDL) process is used for implementing state water quality standards, i.e., it is a planning process that will lead to meeting the water quality standards in *water quality limited receiving water bodies*. It, *de facto,*

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[2] Novotny, V. et al. (1997) *Use Attainability Analysis: A Comprehensive UAA Technical Reference*, Water Environment Research Foundation, Alexandria, VA

[3] Committee to Assess the Scientific Basis of the TMDL Approach to Water Pollution Reduction (2001) *Addressing the TMDL Approach to Water Quality Management.* National Academy Press, Washington, DC

[4] US Environmental Protection Agency (1994) *Water Quality Standards Handbook, 2nd ed.*, EPA-823-b-94-005A, Office of Water, Washington, DC

presumes that the statutory designated use and corresponding standards are attainable. In instances where attainability of the designated use and corresponding standards is in question, a UAA should precede the TMDL. Water quality limited segments have been specifically defined *as those segments that do not or are not expected to meet applicable water quality standards even after the application of technology - effluent limitations required by Sections 301(b) and 306 of the Clean Water Act* (USEPA, 1994). The USEPA Handbook[4] specifies that attainability or nonattainability of designated uses and their relevant standards are judged based on physical conditions, natural or irretrievable chemical conditions, and widespread and substantial socio-economic impact

Description of Clear Lake (Lake County, CA) – Water Uses

Clear Lake located in Lake Country in Northern California is the largest fresh water lake located entirely within the borders of the State of California. The lake covers approximately 176 km^2 (68 sqmi) and has a shore line of about 160 km (100 mi) (Figure 1). The average depth of the lake is 8.2 m (27 ft) and the maximum depth is 18.3 m (60 ft). The lake is 30 km (18 mi) long. Figure 1 shows the area of the lake and its tributaries. The lake's only outlet is Cache Creek. The water system of the lake and its tributaries has been extensively modified.

The lake is a popular tourist destination and is renowned for its scenic shoreline and recreational fishing. It has been used by Native Americans for millennia[5]. European settlers entered the watershed in mid 19th century, being attracted by rich mineral deposits and mercury mining became the main industry shortly after their arrival. The population of Lake County has increased from about 2,000 in 1850 to over 55,000 in 1999[5].Volcanic activity created mineral deposits, hydrothermal systems and the watershed has abundant mineral springs.

Originally, the watershed was significantly covered by wetlands that provided buffering. However, over the years 85% of the original wetlands had been progressively drained and converted to economic land uses such as orchards and vineyards. Today, only a small fraction of the original wetland area remains. Wetlands provide protection of the lake against pollution by suspended pollutants and nutrients. In contrast, when wetlands are drained and modified to economic agricultural and silvicultural uses, a large mass of nutrient pollution is transferred from the drained hydric soils to the receiving waters.[6]

The watershed contains a high proportion of forested land, orchards and vineyards, and cropland area (Figure 2). The forested land is logged and roads have been built to transfer logs to saw mills. Forest fires that do occur in the watershed also emit significant amounts of pollutants and leave the land temporarily unprotected against erosion. The land use in the watershed contains approximately 64.3% of forest and shrub land, 26.8% of pastures and other grassland, 5.9% planted orchards, and about 2%

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[5] Suchanek, T.H. et al.. (2002) Evaluating and Managing a Multi-stressed Ecosystem at Clear Lake, California: A Holistic Ecosystem Approach, in *Managing for healthy Ecosystems: Case Studies,* CRC Press, pp. 1233-1265

[6] Novotny, V. (2003) *Water Quality: Diffuse Pollution and Watershed Management,* J. Wiley & Sons, Hoboken, NJ

residential/commercial land. Other land uses, including wetlands and open water (excluding the lake), cover the remaining 1 % of the watershed area[7]. Current existing wetlands occupy only 0.04% of the watershed land area.

The lake watershed supports extensive agricultural production, including pear, walnut, grapes and wild rice. The lake also supports a commercial fishery, the only commercial fishery on California lakes, and extensive recreational fishing for bass and catfish. The lake is also heavily used for contact and non contact aquatic recreation[5].

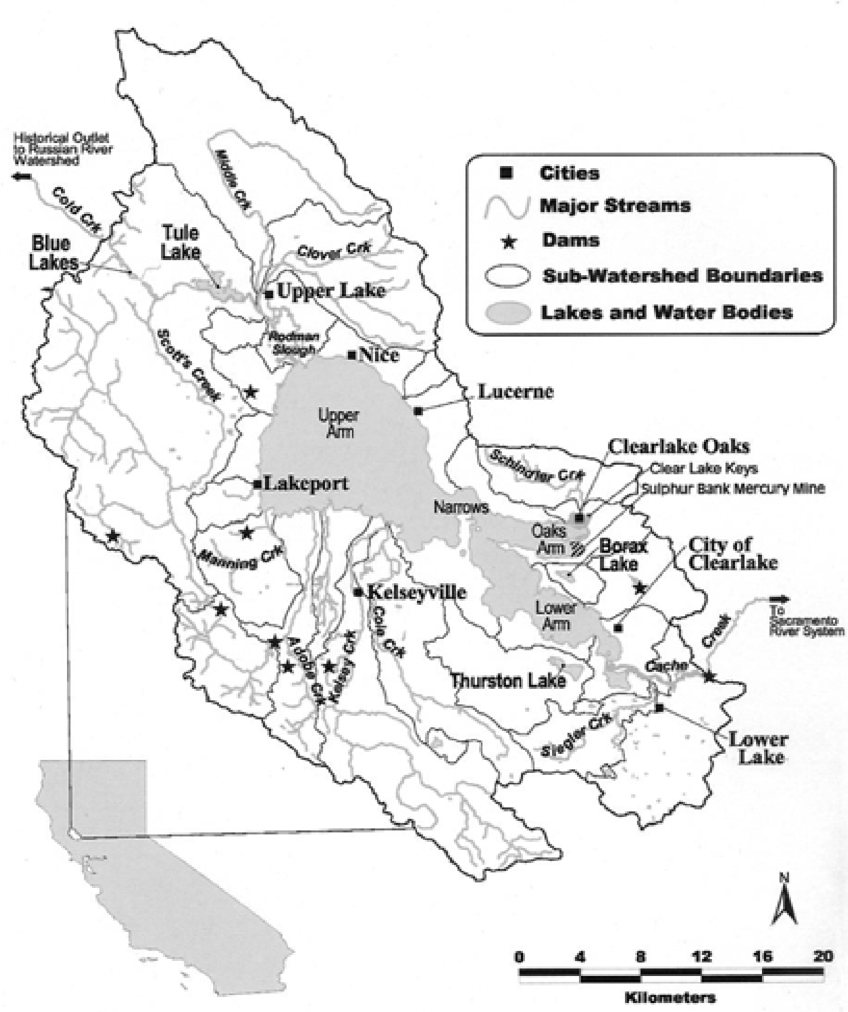

Figure 1 Clear Lake watershed map (Suchanek et al.[5])

[7] Tetra Tech (2004) *Total Maximum Daily Load for Nutrients in Clear Lake, Lake County, California, technical Report,* prepared for Central Valley Regional Water Quality Control Board, Rancho Cordova, CA

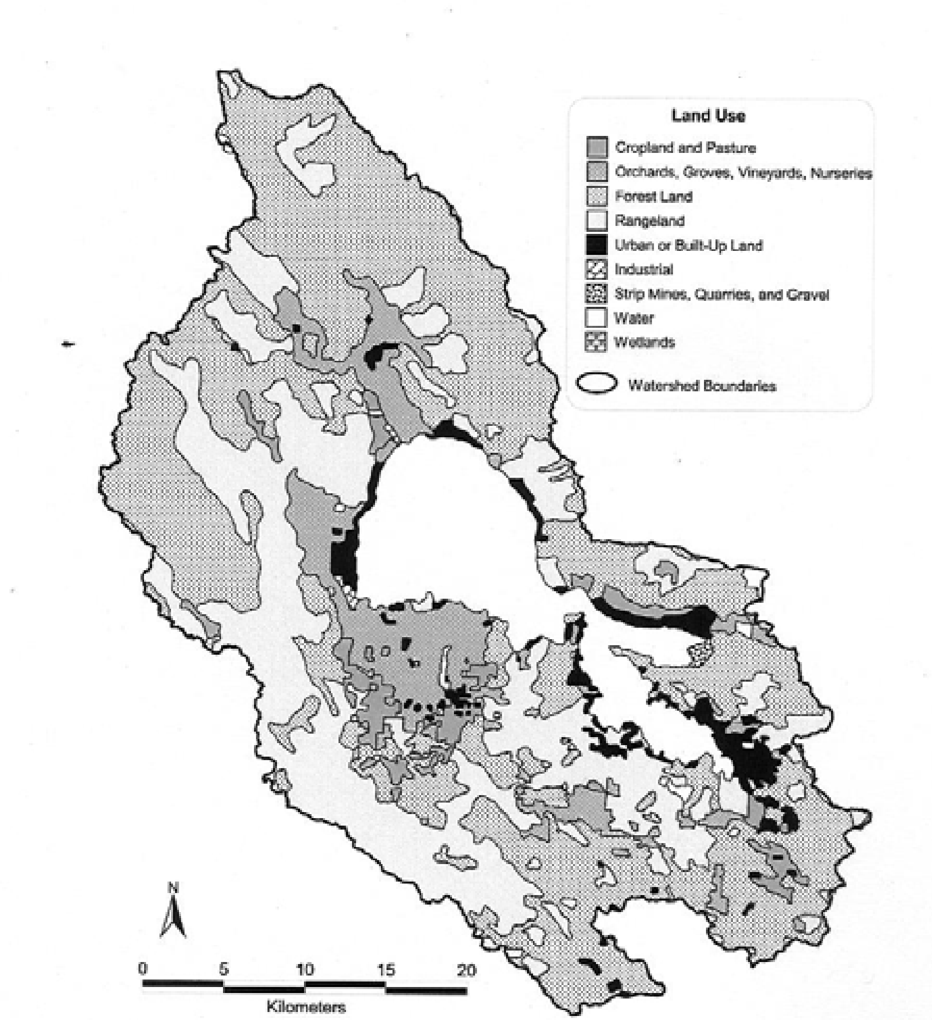

Figure 2 Land use in the watershed in 1999 (from Suchanek et al.[5])

According to USGS sampling of sediment cores, Clear Lake is believed to be the oldest lake in North America, with the sediments dating back about 500,000 years. In contrast, the land which is now covered by the Great Lakes was a prairie 100,000 years ago and the present form of the Great Lakes was formed 15,000 years ago by opening the St. Lawrence River outlet by the receding glacier.

Brief Water Quality Assessment

The water quality situation of Clear Lake is described in the Suchanek et al. [5] and Tetra Tech[7] reports and is briefly summarized below:

1. The lake has been found to be naturally eutrophic, implying that even before the European settlers moved in and converted the lands to the economic (agricultural, mining, and urban) uses, algal blooms due to nutrient enrichment in the water column and sediments were common. The watershed has phosphate rich soils. This finding alone should have been a stimulus for conducting the Use Attainability Analysis before embarking on the TMDL. UAA would have then lead to defining the appropriate uses for the lake and standards to achieve these uses. The number one reason that allows "pre-processing" of the standards and criteria before a TMDL is undertaken is "*Naturally occurring pollutant concentrations prevent attainment of the use"* (40 CFR 131).
2. The historical accounts indicate that prior to the European settlement the lake was populated by macrophyte plants. Larger sediment loads were released into the lake by mining activities and logging, increased turbidity shaded the plants that were then replaced by phytoplankton algae[7].
3. Due to anthropogenic watershed and lake water system modifications the nutrient loads and concentrations in the lake have been increasing, reaching periodically hypereutrophic conditions (Figure 3). Hypereutrophic conditions are characterized by development of obnoxious mats of scum forming blue-green algae, and anoxic conditions in the lower depths of the lake. The density of blue green algae was reasonably correlated to TN and TKN concentrations but very poorly correlated to TP and ortho-P[7].

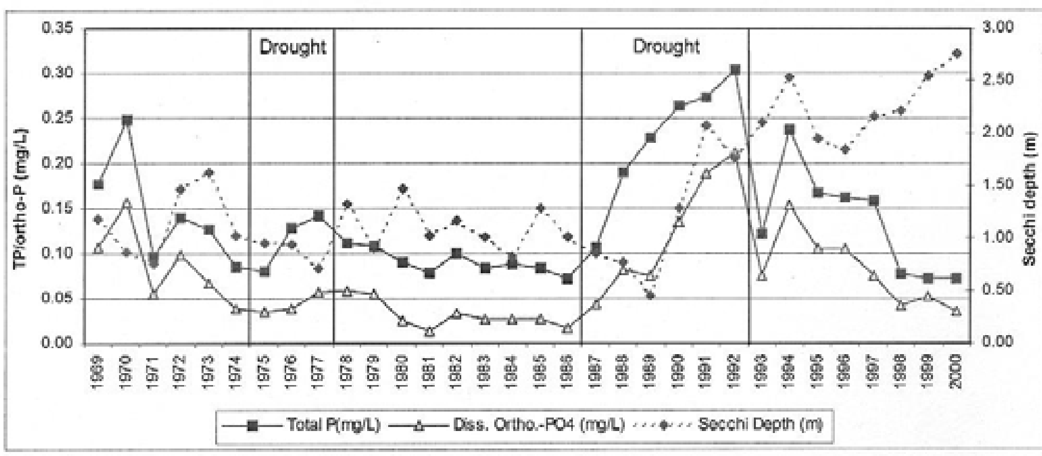

Figure 3 Annual average Secchi depths, total phosphorus, and ortho-phosphate concentrations at the lake monitoring Station CL1[7]

4. Phosphorus concentrations in the water column and sediment are very high, due to the influx of phosphate rich soils by erosion and release of phosphorus from the sediment. The average lake water concentrations of phosphorus between 1969 and 1987 were around 0.1 mg/L, dissolved orthophosphate was in the same period between 0.03 to 0.1 mg/L. The borderline limiting concentration of phosphorus between the mesotrophic and eutrophic conditions is 0.02 mg/l, or five times

smaller[8]. In the drought period of 1987 - 1993, Total Phosphorus concentrations reached 0.3 mg/L and peaked at 0.6 mg/l [9]. However, contrary to common knowledge, the average transparency of the lake has dramatically improved and was high during the period of the highest phosphorus concentrations in the 1991-1992 period. Secchi disc transparency of 2 meters is a borderline between the mesotrophic and eutrophic conditions (see Table 1); therefore, the lake did not appear to be hypereutrophic that would be expected from the high phosphorus concentrations. However, average transparency numbers may be misleading. Even in the "good" years between 1991 and 2000, transparence always dropped in the summer productive period below 2 meters as documented on Figure 3.1 in the Water Quality Control Board report[9].

Table 1 Symptoms of eutrophic conditions[8]

Total P	> 20 μg/l
Chlorophyll – *a*	> 10 μg/l
Secchi disc	< 2 m
Hypolimnetic oxygen	<10 % of saturation

This contradiction between the high phosphorus concentrations and higher clarity (low turbidity) is difficult to explain but the following reasoning may be offered:

- It was nitrogen and not phosphorus that controlled the trophic status of the lake, and/or
- Another compound, an algaecide, may have been present in water, inhibiting algal development.

Clarity of the lake has improved dramatically after 1991.

5. Because of very high phosphorus concentrations it is clear that the lake is nitrogen limited, i.e., under eutrophic conditions the concentrations of algal biomass would be correlated to and could be controlled by nitrogen concentrations. However, under hypereutrophic conditions, some blue-green algae can fix atmospheric nitrogen. In spite of the common knowledge that Clear Lake is nitrogen limited, this reviewer could not find in the report or over the Internet adequate information on actual concentrations of nitrogen during the summer periods. Figure 3-5 in the Tetra Tech report presents the average monthly N:P ratios in the July to November period ranging from 3 to 5. This would indicate that the Total Nitrogen concentration in the lake could be between 0.3 to 0.5 mg/l during the "normal' periods and >1 mg/l in drought years. Based on the classic Sawyer

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[8] US Environmental Protection Agency (1974) *The Relationships of Phosphorus and Nitrogen to the Trophic State of the Northeast and North-Central Lakes and Reservoirs.* National Eutrophication Survey Work. Pap. 23, Washington, DC

[9] Central Valley Regional Water Quality Control Board (2005) *Amendment to Water Quality Control Plan for the Sacramento River and San Joachim River Basin For the Control of Nutrients in Clear Lake.*

study of Wisconsin lakes[10, 11] the borderline Total N concentration between mesotrophic and eutrophic conditions is 0.3 mg/l of the total inorganic nitrogen (ammonium + nitrate). Thus, it may be more efficient to control nitrogen concentrations in the lake (or both nitrogen and phosphorus) rather than focusing the efforts on phosphorus only. Blue green algae concentrations are far better correlated to TN than to phosphorus concentrations, to which they are not correlated at all, as documented on Figure 3-7 of the Tetra Tech TMDL report.

6. Nitrogen fixing during hypereutrophic conditions represents a significant portion of the nitrogen load to the lake. The Tetra tech study[7] claims that during the occurrence of the blue green algae, more than 40% of nitrogen load is by algae fixing the atmospheric nitrogen. This again may confirm that the lake is nitrogen limited.
7. Periodically, blue green algae occur in the lake during spring, summer and fall. The TMDL reports[7,9] claimed that there were no nuisance blue green algal development observed in the period of 1985-1989. This period was defined in these reports as a "period of compliance". There are three species of scum forming blue – green algae found in the lake. The most troublesome is *Microcystics which* is a particularly buoyant species that creates obnoxious odors and occurred in extreme larger numbers in 1991[5,12].
8. Mining for gold (1 historic mine) and mercury (6 mines) has contaminated the lake with mercury and arsenic. At the end of the 19th century, mercury mines in the watershed produced almost 10% of the total US mercury output[5]. It should be pointed out that both mercury and arsenic are algaecides. Mercury can also undergo methylation in the lake sediments producing highly toxic methyl-mercury compounds. Fish contamination by mercury has been measured since 1970s[5]. The loads of mercury may still be continuing because the element is in the soil of the watershed and in the old mine spoils and it is brought into the lake and its tributaries by erosion. The largest mercury mine in the watershed has been declared by the USEPA as a Superfund site.

Beneficial Uses of Clear Lake

The beneficial uses listed in the Central Valley Regional Water Quality Control Board report[9] include water supply (existing but impaired), agriculture, contact and noncontact recreation (existing but impaired), freshwater habitat (existing but impaired), warm water freshwater habitat and spawning, wildlife habitat, and commercial and recreational fishing. The excessive algal development makes treatment of water from the lake for drinking very difficult and compliance with the drinking water quality standards cannot be met. Obnoxious algal scum mats inhibit recreation and decaying settled biomass and

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[10] Sawyer, C.N. (1947) Fertilization of lakes by agricultural and urban drainage, *J. N.E. Water Works Assoc.* **51:**109-127

[11] Krenkel, P.A. and V. Novotny (1980) Water Quality Management, Academic Press, New York

[12] Richerson, P.J., T.H. Suchanek, and S.J. Why (1994) *The Causes and Control of Algal Blooms in Clear Lake, Clear Lake Diagnostic/Feasibility Study for Clear Lake, California,* prepared for USEPA, Region IX

decomposition processes in the benthic layer create anoxia near the bottom. Algal respiration during night hours may create low oxygen concentrations that cause fish-kills.

TMDL

The TMDL process, as embedded in the Section 303(d) of the Clean Water Act, was developed primarily for control of pollutants from point sources and is best applied to very low flow conditions. Applications of the TMDL have encountered numerous problems when applied to control of nonpoint sources. But in general, the process is the same for all sources and includes the following steps:

1. The uses of the water body are defined
2. Numeric standards protecting the uses are defined
3. Loading capacity of the water body is calculated by a calibrated and verified model
4. The loading capacity minus a Margin of Safety is allocated between the point, nonpoint and background sources.

Target (Goals)

There is no numeric standard for nutrients for the Clear Lake. The Basin Plan contains a narrative objective for "biostimulating substances" which states that "*Water should not contain biostimulating substances which promote growths in concentrations that cause nuisance or adversely affect beneficial uses"*[9].

If the standards or criteria are narrative, the TMDL requires development of a "translator" that, using a surrogate parameter, converts the narrative statement into a numeric standard. For nutrients, the criteria can be developed for the limiting nutrient, Secchi disc depth, or for chlorophyll-a. Chlorophyll-a was selected as the target parameter for Clear Lake.

However, here is where the TMDL preparers struggled. They hypothesized that the "usual" goal for lakes and reservoirs, such as creating mesotrophic conditions, was unattainable for Clear Lake (this should have been established by the Use Attainability Analysis). Under this situation the question they faced was "which *bad status of the lake* is acceptable and which is not?"

The TMDL preparers selected then highly eutrophic to hypereutrophic status without excessive blue green algae growths as acceptable and the hypereutrophic status with excessive blue green algae as not acceptable. Tetra Tech[7] then developed and used models from the USEPA Toolbox (see next section) to define a Chlorophyll target for the lake. Using the period 1985 – 1989 as "compliant" period they noted that the highest simulated chlorophyll concentration during this period was 73 μg/L. Note that the information in Table 1 would indicate that this chlorophyll concentration would be in the high eutrophic or borderline hypereutrophic level. The Water Quality Board report[9] made then a scientifically dubious judgment call that"*based on this simulation, it is expected that chlorophyll levels can reach as high as 73 μg/l and no nuisance blue green algal blooms would occur in the lake*" and established this chlorophyll concentration as the target of abatement in TMDL and then based the maximum phosphorus load on the simulation. This judgment was made, knowing that there is little or no correlation of blue green algae to phosphorus concentrations and the lake is nitrogen limited.

Sources of nutrients

Suchanek et al. [5] and Tetra Tech [7] provided a detailed listing of sources of nutrients:

Anthropogenic External Stresses

- Forest fires
- Logging and deforestation
- Dam construction and other modifications of tributaries
- Mining operations (sulfur, mercury)
- Pesticide applications to the lake and watersheds
- Wetland drainage and conversion to agriculture and silviculture
- Dredging and filling
- Creek bed and shoreline modifications
- Nonpoint sources
  - Agriculture
  - Cattle and Sheep Grazing
  - Residential construction
  - Off-road vehicle erosion and washoff of dust
  - Septic tanks
- Urban point sources

Controllable and uncontrollable sources of pollution

A distinction should be made between the controllable, partially controllable and uncontrollable sources. All point sources subjected to NPDES permitting are controllable. This includes urban and mining sources. Regarding nonpoint source pollution from forest logging and agriculture/silviculture, the Northern California Federal District Court has asserted the EPA right to withdraw federal funds from the state if the nonpoint source management required by the TMDL is not incorporated in plans and implemented by the state[13]. Therefore, nonpoint pollution is controllable.

Internal sources

Both phosphorus and nitrogen are stored in the sediments. The quantities are large. Tetra Tech estimated that during drought periods, internal rather than external loadings are the main source of phosphorus. Then internal loadings amplified the algal blooms.

It should be pointed out that the lake sediments can also be a significant sink of nitrogen. If the interstitial layer between the sediment and water is aerobic, simultaneous nitrification-denitrification can take place. In this process, the concentration gradient between the bulk of sediment and the sediment-water boundary layer drives ammonium from the sediment into the interstitial oxic layer where it is rapidly nitrified to nitrate. The nitrate gradient is in the opposite direction, from the top of the sediment down where in

[13] Pronsolino et al. vs. Marcus and Bower, 2000

the anoxic sediment layer nitrate is denitrified to nitrogen gas and lost from the lake system. Simultaneous nitrification – denitrification can remove significant quantities of nitrogen from the lake[6,14]. Similar losses were measured in the nitrogen limited lagoon of Venice. The key for a significant nitrogen loss from sediments is keeping the bottom interstitial layer aerobic. Phosphorus can be removed from the sediment only by leaching of the soluble orthophosphate into water or by scouring the sediment, an unlikely phenomenon in Clear Lake. Phosphate and ammonium leaching from sediments is 3 to 5 times greater if the interstitial layer is devoid of oxygen. Phosphorus release is also controlled by pH, iron and aluminum content of sediments and other factors. If the water-sediment interstitial layer is anoxic, no simultaneous nitrification-denitrification occurs and ammonium release increases. [15,16]

Loading and Loading Capacity Estimation - Models

The Tetra Tech draft modeling report[7] begins Chapter 4 on modeling with the following statement: *Prior research and a review of recent data conducted for this TMDL suggests that nuisance blue – green algae blooms are facilitated by high phosphorus loading to the lake ..... a correlation between high in-lake phosphorus concentrations due to internal loading and algal productivity has been identified…*

This statement, that sets the focus of the modeling and the entire strategy of the TMDL on phosphorus, is contradicted by Figure 3-7. This figure shows that *there is no correlation or any reasonable relationship between the TP or ortho P and blue - green algae in the lake*. It cannot be, the lake is nitrogen limited. At the monitoring station CL1 (middle of the lake) the R-square coefficient between the blue-green algae and TP was 0.1 and that for ortho P was less than 0.05. On the other hand, the correlation of blue-green algae and TN and TKN produced R-square of about 0.48 and 0.45, respectively. Even when the data were separated into wet and dry years, correlations to phosphorus were very poor with a maximum R-square of 0.25 while R-square for TN was 0.6 for the dry years. The report has then tried to find a relationship between the Secchi disc, phytoplankton and annual average Total P in Appendix E and claimed that there is one when there was none.

After this preamble almost all attention of the modeling was focused on finding a relationship between the chlorophyll a and phosphorus, which may seem to be elusive from the beginning. It is hard to pinpoint the reasons for eliminating nitrogen from consideration. The report continues with an extensive discussion of the criteria for model selection.

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[14] Keeney, D.R., S. Schmidt, and C. Wilkinson (1975) *Concurrent Nitrification-Denitrification at the Sediment-Water Interface as a Mechanism for Nitrogen Losses from Lakes.* Tech, Rep. 75-07, Water Resources Center, University of Wisconsin, Madison, WI

[15] Selig, U. and G. Schlungbaum (2003) Characterization and quantification of phosphorus release from profundal bottom sediments in tow dimintic lakes during summer stratification, *J. Limnol.* **62**(2):151-162

[16] Board of Agriculture (1993) *Soil and water Quality: An Agenda for Agriculture,* The National Academies Press, Washington, DC

Tetra Tech selected two models, the loading model and the lake model. The models selected are public domain models that Tetra Tech and US EPA laboratory in Athens, GA are now incorporating into the US EPA TMDL Modeling Toolbox. However, at the time of writing this review, the latest versions of the models were not downloadable from the US EPA web site. This is not a problem in this review because the reviewer is familiar with and has used with co-workers the previous versions of the models.

Watershed Loading Model – Loading Simulation Program C++ (LSPC)

The LSPC model integrates the Hydrological Simulation Program – FORTRAN with GIS. HSP-F has been used for at least 25 years and evolved from the Stanford Watershed model. The model is relatively difficult to set up, requires extensive watershed information, many calibration and verification runs, and a knowledge on many parameters and coefficients that is not always readily available. The model has extensive capabilities, has been tested and generally accepted. It is labor intensive and can be set up and run only by experienced modelers.

The HSP-F contains three application modules. One simulates loadings from pervious surfaces, the second from impervious surfaces, and third models the water and pollutant routing in the streams. The model dynamically estimates time series of water loads due to precipitation, sediment erosion and movement from lands, and pollutant loads. Water quality constituents can be simulated in a simple way by relating them to sediment loads with potency factors or by a more complex adsorption-desorption concept. Both concepts were used in modeling loads of pollutants to Clear Lake.

The use of the model necessitates dividing the watershed into subwatersheds and segments. The Clear Lake watershed was subdivided into 49 segments. Ideally, these segments should be homogenous or their characteristics can be lumped together to represent a homogeneity. Each segment/land use is divided into pervious and impervious land units for modeling. For each segment a uniform soil type is assigned.

Water and pollutant loading was then routed towards the lake by the third component of the LSCP model.

The experience with modeling water quality with HSP-F has not been always good, especially when only few data points were available to validate the model. This is also documented in the Tetra Tech report.

Environmental Fluid Dynamics Code (EFDC)

EFCD was used for hydrodynamic and water quality modeling of Clear Lake. This compendium of dynamic water and quality models simulates hydrodynamics, salinity, temperature, and cohesive and non – cohesive sediment transport as well as near and far field effects of pollutant discharges, eutrophication, and the fate and transport of toxic substances.

The lake was discretized into a computational grid. The model sequentially solved in small time steps differential equations describing water movement and fate of the water quality constituents and their effect on algae. The sixteen water quality and algae constituents modeled by EFDC are described in the Tetra Tech report. To enhance the modeling capabilities, Tetra Tech added nitrogen fixing by blue-green algae and luxury phosphorus consumption in order to better represent the conditions in the lake. Luxury uptake represents a phenomenon in which algae can absorb higher quantities of nutrients without a corresponding growth increase.

The entire model (both LSPC and EFDC) was run for a period extending 1985 - 2002. Of the hundreds of calibration runs conducted, only a few runs resulted in acceptable balances of all parameters (chemical and biological) with respect to monitoring data (Tetra Tech report, p.51). The model was not directly calibrated and validated for observed algae data, because algae observations were in the form of cell count. In contrast, model results were estimated in terms of biomass as carbon.

Modeling Outcome – Load Allocation

The water quality model simulated chlorophyll concentrations. As stated above the chlorophyll model was not calibrated and verified by measurements, hence, no plots of measured and calculated chlorophyll were presented in the report. Then it was, somewhat arbitrarily, decided that the chlorophyll concentration of 73 μg/l calculated in the last year of the "compliance" period, is the goal. The 73 μg/l of chlorophyll is a borderline hypereutrophic condition.

Following this definition of the goal, it was decided that, in spite of all evidence presented in the reports that pointed to a nitrogen limited water body and no statistical link of the blue green concentrations to phosphorus concentrations, phosphorus was made the target compound. It just happened that during 1985 -1991 period the average phosphorus load was calculated by the models was 411 kg/day. Nitrogen load estimation was not reported. The external load considering pre-European land use distribution was calculated as 370 kg P/day. However, considering the existing channel and shoreline modifications, it was asserted that the pre-European external load would not meet the 73 μg/l target concentrations. A 40% reduction of external phosphorus loading would result in the chlorophyll concentration of 64.9 μg/l, which would provide a Margin of Safety of 8%. This 40% required external phosphorus reduction was then incorporated into the basin TMDL plan.

No nitrogen reduction was estimated in spite of the fact that nitrogen is limiting nutrient.

Complexity of the Modeling Effort – Are the Models Appropriate?

The Committee on the Scientific Basis of the TMDL Approach[3] has spent considerable time analyzing the adequacy and appropriateness of the water quality modeling tools provided by US EPA. The following discussion will present some of the problems. Such discussion at this time may be philosophical and to some degree pointless. One has to realize the fact that practicing TMDL developers and state agencies would be reluctant to use models that are not yet approved and extensively tested by the US EPA. Hence, TMDL preparers are left with using models based on almost thirty year old concepts. Only recently (Fall 2005), US EPA has issued a call for extensive research in the STAR (Science to Achieve Results) program for the new generation of models that would better represent the reality and complexity of layered ecological hierarchical models such as eutrophication and hypereutrophic models and linking the biotic communities to stressors.

The loading and water quality models used by Tetra Tech are based on older modeling approaches that were shown in recent literature to fail when modeling complex biotic phenomena such as hypereutrophication. The EFDC model in particular is a very complex dynamic *deterministic* model that performs a mass balance of each computation element described by linear differential equations (or equations that were made linear). The deterministic, sometimes called mechanistic models describe the processes in detail. For each set of inputs there is one output. The concentrations of algal biomass are tied by the linear growth rate to the concentrations of the stimulants, i.e., nutrients. Therefore, if a concentration of phosphorus is entered the model will provide an answer that will vary with each change of the input. The magnitude of the output will increase proportionally to the increase in the input and vice versa. Proportionality is the fundamental property of linear deterministic models.

Eutrophication and hypereutrophication do not follow this concept, as documented extensively in recent US and European literature[17, 18, 19]. The growth of algae is not linearly tied to the concentrations of nutrients and there are thresholds. The aquatic plants and biota develop in relatively stable domains that may be dominated by one type of organisms. The well known succession is clear water with macrophytes submerged plants (oligotrophic) → a system dominated by diatoms (meso-trophic) → a system dominated by green algae (eutrophic)→ finally by blue green algae (hypereutrophic). Actually, the succession can further continue to a wetland system and finally to dry land. Each domain exhibits resiliency against change and when a threshold of resiliency is passed the system shifts to the next domain. Resiliency works in both ways. For example, when the system becomes dominated by blue-green algae it may not be possible to gradually return it back to eutrophic or mesotrophic conditions in proportion to the reduction of the nutrient load and the status may become irreversible or partially reversible[17]. The models representing these systems and shifts between domains are nonlinear.

Scheffer et al.[18] and Folke et al.[19] describe these alternative stable states, starting with the clean lake. The pristine state of most shallow lakes has clear water and abundant submerged vegetation. Remarkably, water clarity often seems to be hardly affected by increasing nutrient inputs until a threshold is passed at which the lake becomes turbid. With increase in turbidity, submerged macrophytes disappear and the biomass is dominated by phytoplankton in which green algae may dominate. Reduction of clarity has an impact on animal diversity that kept phytoplankton in check and a gradual reduction of nutrient input will not result in a corresponding reduction of turbidity. Restoration of eutrophic lakes requires far more than just reduction of nutrients. A case in point is a restoration of Lake Delavan in south central Wisconsin that required a suite of measures to repair the highly eutrophic to hypereutrophic status of the lake, including significant reduction of nutrient inputs, sealing the bottom release of phosphorus by application of alum, eradication of carp, hydraulic changes of currents, and restoration of upstream wetlands[3]. As a matter of fact, the largest algal bloom of blue-green algae

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[17] Carpenter, S., R., D. Ludwig, and W.A. Brocks (1999) Management of eutrophication for lakes subject to potentially irreversible change, *Ecological Applications,* **9**(3):1-16

[18] Scheffer, M. et al. (2001) Catastrophic shifts in ecosystems, *Nature* **413**(11):591-506

[19] Folke, C. et al. (2002) *Resilience and Sustainable Development.* The Environmental Advisory Council to the Swedish Government,

occurred after the phosphorus loads were significantly reduced. Some measures that may be needed can be called a "shock therapy"[18].

Conclusion

Developing the TMDL plan for Clear Lake is undoubtedly a difficult case but the TMDL for Clear Lake raises more questions than answers. The study had to be done, the social and economical values of the lake are high and the state was required to act. In overall, the TMDL preparers tried to develop a plan which they themselves consider as a first step and proposed an adaptive implementation. This implies that after a certain period after the first step actions are implemented the TMDL will be revisited and the plan revised to reflect the success, or a lack thereof, of the plan. They used the best public domain and USEPA endorsed and (to be) distributed modeling technology. They followed established procedures and court tested steps.

However, the state-of-the-art of knowledge about lake eutrophication and hierarchical progression and resilience of its states and modeling technology has now improved and the 30 years old TMDL modeling has not yet caught up. The problems and doubts should be identified but corrections of these deficiencies are uncertain and would require a comprehensive research effort, not just a TMDL that was lacking data for calibration and validation and establishing initial conditions.

1. The TMDL arbitrarily failed to incorporate the fact that the lake is nitrogen limited and there is very little correlation of blue-green algae concentrations to phosphorus.

   Arguments will be made that blue green algae can fix atmospheric nitrogen and the only reasonable alternative is to control phosphorus even when the outcome of the phosphorus controls is highly uncertain. This argument is contradicted by many efforts to control nitrogen limited water bodies by reducing nitrogen loads such as the European nitrate directive or the starting efforts to control anoxia in the Gulf of Mexico. Nitrogen load control has already been partially successful to reduce hypereutrophic (in the 1980s) Lagoon of Venice to a lower eutrophic, approaching mesotrophic status today. The surface area of the lagoon is about 500 km^2.

2. The resiliency of the hypereutrophic status will require more drastic reduction of nutrient loads and other measures to bring about an improvement of the hypereutrophic status.

3. Lake restoration is a comprehensive effort and focusing on one non limiting nutrient will not be successful. Not addressing nitrogen limitations and presenting alternatives that would consider nitrogen as a controlling parameter is puzzling. The fundamental rule of any lake management is focusing on the limiting nutrient first. Ideally, both nutrients should have been considered.

   Ideally, reduction of both nitrogen and phosphorus loads may be required. Nitrogen loads can be reduced by controlling nitrogen in effluents, e.g., by converting the treatment plants to denitrifying and phosphorus reducing Bardenpho treatment plans and, more efficiently, by restoring and recreating riparian wetlands that provide an efficient buffer along the headwater streams. The lake itself by simultaneous nitrification/denitrification can remove more than 1/3 of the internal load provided that anoxia in the lower zones of the lake is avoided, which may require engineering measures. Keeping the bottom layer oxic will also reduce the internal phosphorus load.

4. Biological methods of fish management have also been found successful in the overall restoration efforts.

5. The stated goal of eutrophic to hypereutrophic goal of 73 μg/l of chlorophyll is a dubious goal. Even if the lake responds proportionally (I have serious doubts about the proportionality scenario) to the reduction of the phosphorus inputs and the borderline hypereutrophic status is achieved, the lake will hardly support the designated uses. There is too much variability involved. The selected "compliance" period had average Secchi Disc depths about 1 to 1.5 meters that are not conducive for swimming and hardly could support good quality fish. The water quality may not be suitable for water supply and the toxins produced by the blue green algae may be dangerous to human health when ingested during swimming.

6. A Use Attainability Analysis should have preceded the TMDL.

7. The TMDL planner and the state and local agencies implementing the plan must realize the fact that more reductions and actions will be required than that estimated by linear models. The uncertainties with trying to solve the problem with reducing phosphorus loads only are so large that the end results are in doubt, especially when considering the adopted relatively small margin of safety (8%).

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